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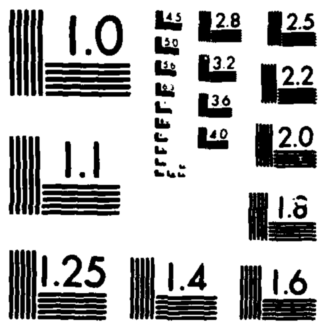

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STANFORD ELECTRONICS LABORATORIES
DEPARTMENT OF ELECTRICAL ENGINEERING
STANFORD UNIVERSITY · STANFORD, CA 94305

JSEP FINAL REPORT

1 May 1984 through 30 April 1985

J. S. Harris, JSEP Principal Investigator
S. F. Lundstrom, JSEP Program Director

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is the final report of the research conducted at the Stanford Electronics Laboratories under the sponsorship of the Joint Serivces Electronics Program from May 1, 1984 through April 30, 1985. This report summarizes the areas of research, identifies the most significant results, and lists the dissertations and publications sponsored by the contract (DAAG29-84-K-0047).

Abstract

This is the final report of the research conducted at the Stanford Electronics Laboratories under the sponsorship of the Joint Services Electronics Program from 1 May 1984 through 30 April 1985. This report summarizes the areas of research, identifies the most significant results, and lists the dissertations and publications sponsored by the contract (DAAG29-84-K-0047).

Key Words and Phrases: None.

Table of Contents

This work was supported by the Joint Services Electronics Program, contract DAAG-29-84-K-0047.

1. Introduction

This report summarizes the activities in the research programs at the Stanford Electronics Laboratories sponsored by the Joint Services Electronics Program under contract DAAG29-84-k-0047. This contract is monitored by the Army Research Office, Research Triangle Park, North Carolina.

This report covers a transition period in our JSEP program as several projects were phased out and others re-directed. This was done to align the current year's interim program with the continuing program based upon our recently submitted and approved 3 year proposal.

The research program is divided into two main areas:

- Semiconductor Materials, Circuits and Processes
- Information Systems

The work units and tasks within each of the above areas are summarized below, together with the investigators directing each task.

1. Semiconductor Materials, Circuits and Processes
   a. Complementary MOS Device and Material Physics at 77 K (J. Plummer and K. Saraswat)
   b. Physics of Compound Semiconductors (J. Harris)
   c. The Chemical and Electronic Structure of Refractory Metal-GaAs Interfaces (R. Helms, W. Spicer and I. Lindau)
   d. Channeling Radiation for the Study of Properties of Materials (R. Pantel)
2. Information Systems
   a. Real Time Statistical Data Processing (T. Kailath)
   b. Data Compression for Computer Data Structures (J. Gill)

2. Significant Results

The three most significant accomplishments, as determined by the JSEP Principal Investigator and Director, are summarized as follows:

- *Complementary MOS Device and Material Physics at 77 K*

  The objective of this work is to investigate the fundamental physics of operation and potential of silicon CMOS devices operated at 77 K for VLSI circuits. During the past year, experimental CMOS devices have been fabricated with channel lengths from < 0.5 mu to 50 mu and experimentally characterized over the 77 - 350 K temperature range. The following results have been achieved:

  1. A new understanding of small geometry device physics at low temperatures has been achieved through experimental measurements and through modifying a 2D device simulator (GEMINI) to allow computer simulation of device characteristics at low temperature. The results indicate that the basic physical mechanisms which dominate short channel effects at room temperature, also determine short channel behavior at low temperature. Quantitative differences in the magnitude of such effects favor low temperature operation. A paper has been submitted to IEEE Transactions on Electron Devices, describing this work.

  2. A new physical model for quantitative modeling of hot carrier effects in MOSFETs has been developed and implemented in a 2D device simulator jointly with Intel Corporation. The model makes use of the Shockley "Lucky electron" model and couples it with a Maxwell-Boltzmann energy distribution for the electrons to successfully predict hot carrier effects over the full 77 - 350 K range. Use of this model, coupled with experimental measurements has suggested appropriate power supply voltages to use in CMOS circuits operated at 77 K. Two papers have been presented on this work.

- *Physics of Compound Semiconductors*

  This is an entirely new project initiated at the start of this year. The focus of the project is on ultra-small structures and electronic transport and optical properties of these structures. The major JSEP activity during this period has been a theoretical study of transport of 1-dimensional electrons confined by very high magnetic fields. A theory based upon weak coupling between 1-dimensional electrons and the lattice (i.e. polar-optical phonons) has been developed. When the electreons are confined to one dimension, the interacting electron-phonon, or polaron, system has an unusual energy momentum relation with negative effective mass regions. As a consequence, anomolously large space charge regions can form and cause periodic structure in the I-V characteristics of AlGaAs/GaAs heterojunction structures when a magnetic field is applied. This periodic structure was observed by Hickmott et. al., and the magnitude of the oscillations had hitherto not been explained satisfactorily. Three papers have been presented on this work at major international conferences and four papers have been submitted to journals for publication (see publications in Section 6).

- *Real Time Statistical Signal Processing*

  The main focus of this project is the development of high resolution methods for estimating the directions of arrival of narrowband and wideband signals in additive noise. The main accomplishments during the last year were the publication of two very well received journal papers in this area and the completion of the Ph.D. research of M. Wax.

This work focused on the development of an objective tool (based on information-theoretic criteria) for the theory problem of determining the number of signmals impinging on an antenna array. Previous solutions have been either adhoc or subjective. These results are summarized in the Wax-Kailath publication in IEEE Trans. ASSP, April 1985.

A second paper by Shan and Kailath (ASSP, June 1985) partially solves a long- standing problem of combating coherent interference (e.g., "smart" jamming) in adaptive beamforming problems. the effect of the coherence is that the conventional (adaptive) arrays cancel both the interference and the desired signal. For the case of linear array geometries, the above paper describes a 'spatial smoothing' solution that effectively removes the coherent interference.

3. Semiconductor Materials, Circuits and Processes

3.1 COMPLEMENTARY MOS DEVICE AND MATERIAL PHYSICS at 77 K

This portion of the contractual work addresses the issues of: impact ionization current generation; hot carrier transport across the Si/SiO2 interface; and hot carrier trapping in gate insulators. These issues are addressed as they pertain to CMOS FETs, operated at liquid nitrogen temperatures for high-speed, VLSI computer applications.

Progress to date includes definition of novel structures to measure gate current directly on a single, small-dimension FET, and study of the effects of both AC and DC stress on single devices. These structures have been placed in a test pattern for fabrication using the Stanford IC lab facilities, with temperature measurement on our own liquid nitrogen-based temperature control system. The test pattern was completed in August, 1984; the first CMOS run was successfully processed out in October, 1984. Initial measurements were carried out on long and short channel NMOS transistors, over the temperature range 77 - 300 K; these measurements led to the conceptualization of an impact ionization model, which was implemented in the two-dimensional device simulator CADDET. The results from this initial effort were presented at the VLSI Symposium and have been submited to IEEE Trans. on Electron Devices. The paper was entitled, "Characterization and 2-D Simulation of Impact Ionization Current in MOSFETs between 77 and 300 K."

Measurements are presently underway to characterize carrier surface mobility at low temperatures. Physical effects such as surface roughness and coulombic scattering from oxide charges are expected to be more significant at low temperature, but such effects have not been well characterized.

Overall, the work to date has demonstrated that 77 K operation of CMOS VLSI circuits is quite feasible, and, in fact, desirable from the point of view of device and circuit performance. Work over the next year will be aimed at evaluating CMOS latchup and bipolar device performance at low temperature and at devising an optimized technology for low temperature circuits.

3.2 PHYSICS OF COMPOUND SEMICONDUCTORS

One of the major objectives of this task is to investigate transport in 1 and 2 dimensional superlattice structures. One means of simulating 1-dimensional confinement is by applying very high magnetic fields. The high magnetic field confines carriers to a dimension less than their wavelength and thus simulates the confinement by heterojunction potential barriers. Tunneling current through an AlGaAs barrier into lightly doped GaAs grown by MBE was measuured by Hickmott, et al at IBM. They observed periodic structure in the tunneling current with a periodicity of exactly 36 meV, the optical phonon energy of GaAs. The coherence of the oscillations was remarkable and could be observed for as many as 30 periods (>1V). The occurance of these oscillations only under high magnetic fields suggested that the 1-dimensional nature of the electrons might be playing a critical role in the scattering and resultant energy loss of the electrons.

A first order perturbation calculation of the scattering rate for electrons as a function of energy was carried out. The 1-dimensional density of states has a singularity at E=0, thus as the electrons approach the optical phonon energy, there is an infinite number of available states into which to scatter at E=0. Since this divergence indicated that perturbation theory was invalid, a more sophisticated variational calculation of the energies of the electron- phonon, or polaron system, was done. The calculated energy-momentum curve shows significant bending at $k=h\mu$ and that the polaron has a negative effective mass for states just below the phonon energy. In this region, the polaron will have vanishing group velocity and can gain no additional kinetic energy until it emits a phonon. In the Hickmott experiment, the electrons are thus forced to emit a cascade of LO phonons as they cross the depletion region after tunneling through the AlGaAs barrier. When they exit the depletion region with exactly the phonon energy, their velocity is very small and a large space charge piles up. This space-charge causes a voltage shift which modulates the current through the tunnel barrier. In collaboration with C. Hanna and R. Laughlin in the physics department, who have found evidence for current inhomogeneities in the Hickmott experiment, we have modeled the current voltage curves and find excellent experimental agreement with 1-D polaron, inhomogeneous tunneling theory.

The enhancement of the phonon emission process by 1-dimensional confinement may be significant for possible 1-dimensional devices. If the phonon interaction is strong enough, electrons accelerated in large electric fields will not be able to populate electron states above the phonon energy. This would prevent them from transfering to the high mass L-valley, where their velocities would be small. The high field saturation velocity could thus be increased by as much as a factor of two. A paper on the polaron calculation and explanation of the 1-dimensional transport nature of the Hickmott experiment was presented at the March APS Meeting. The quantitative modeling of the Hickmott experiment was presented at the Hot Electrons in Semiconductors Meeting in July. Implications of the 1-D polaron theory for 1-D semiconductor heterostructures were reported at the Modulated Semiconductor Structures-II Conference in September. Four papers have been submited for publication on different aspects of the polaron and 1-dimensional transport in solids.

Toward the end of the current conttract period, the two growth chamber MBE system (purchased under DARPA sponsoship) became operational. The focus of this project will be to fabricate and experimentally investigate the electron transport properties of 1-dimensionall structures grown by MBE or in conjunction with high magnetic fields.

3.3 THE CHEMICAL and ELECTRONIC STRUCTURE of REFRACTORY METAL GaAs-INTERFACES

This program has two major objectives related to contacts between GaAs and Ti (or other group IV, V and VI refractory transition metals). The first relates to the possibility of forming an "ideal" interface to GaAs where the interface formed is atomically abrupt, as the Ti-Si interface is, and the chemical interaction between the Ti and both the Ga and As is sufficiently strong so that near interface nonstoichiometry effects are not important. In this way some of the models for Schottky barrier formation can be tested for a more ideal system than has been possible previously. In addition, Ti has a lower workfunction (electrongativity) and is strongly covalently bonded in contrast to most other metals investigated.

In addition to properties of more ideal interfaces, the properties of Ti-GaAs interfaces with damage or impurities present are also important - both from the point of view of understanding fundamental mechanisms as well as making connection to the rp'evious literature and GaAs contact technology. We are therefore pursuing two parallel investigations - one on ideal GaAs-Ti interfaces, and one on GaAs-Ti interfaces with damage and impurities present.

In the first area we have investigated Ti-GaAs interfaces for n type GaAs. We observe considerable chemical interactions suggesting the formation free Ga, Ti-Ga, and Ti-As compounds. It appears this interaction is laterally homoge- neous but the extent of the reaction is not clear at this point. On the n type GaAs investigated the barrier height is approximately 0.7 eV (pinning at the acceptor level). This appears consistent with recent arguments that suggest that low electronegativity (or low workfunction) metal appear to pin at the acceptor level, whereas high electronegativity metals pin at the donor level.

In the second area we are investigating the effect of native GaAs layers on the interface chemistry and barrier height. To this end we are presently growing and characterizing thin native anodic oxide layers so that the inter- actions between GaAs native oxides and Ti may be fully characterized. One of the difficulties encountered which we are currently investigating is the sensitive nature of these oxides to the radiation employed in the surface spectroscopies used for characterization.

3.4 CHANNELING RADIATION for the STUDY of PROPERTIES of MATERIALS

The channeling radiation spectra were calculated and measured for a GaAs crystal. Observed electron channeling emission peaks were very close to the predicted peaks, but the positron spectra were shifted 10-15% in energy above the calculated values. The latter experiment must be repeated to determine if this shift is real or an artifact of the setup.

Damage induced in an ionic crystal, LiF, using an electron beam was studied by means of channeling radiation. It was found that at a specified dosage the positron emission was much less affected by the damage than electron emission. In addition, emission from (111) planar channeling was less affected than from (100) and (110) planar channeling. These results can be explained in terms of which atoms in the crystal are displaced by the damaging beam and where these displaced atoms are located. An independent measurement of crystal damange will be performed, using x-ray diffraction, to confirm the conclusions obtained from channeling emission.

4. Information Systems

4.1 REAL TIME STATISTICAL DATA PROCESSING

Most of the research effort on the last year has been devoted to deducing an "optimum" solution to the problem of detecting signals and estimating their directions of arrival by an array of sensors. Most previous approaches to this problem have been based on decoupling the detection and estimation problems; the detection problem was formulated independently of the estimation subproblem and solved first by hypothesis testing techniques. Only then, with the number of the signals at hand, was the estimation problem addressed. Though this decoupling may be advantageous from a computational viewpoint, it is definitely not optimal from a performance viewpoint. The two intimately related aspects of statistical modeling - the estimation of the order of the model (the detection problem), and the estimation of the parameters of the model (the estimation problem) - cannot be decoupled if optimal performance is desired.

We have succeeded in developing a new approach to the coupled detection- estimation problem based on a certain so-called AIC and MDL model selection criteria. Unlike the previous approaches, ours is optimal; we prove the consistency of the MDL estimator of the number of signals as well as the asymptotic efficiency of the estimators of the signal parameters and the signal waveforms.

A new DEC VAX 11/750 computer is being brought up and should considerably aid our simulation efforts.

Contacts have been made with people from Navair (Dr. Jim Smith, Dr. W. Alltop) and NOSC (Dr. J. Speiser, Dr. H. Whitehouse), who appear to be quite interested in our results.

4.2 DATA COMPRESSION for COMPUTER DATA STRUCTURES

Hardware design of a bit-slice data compression unit based on the AMD 29116/2910 processor/microcontroller was completed. The unit is designed to implement a version of Ziv-Lempel universal coding discovered by Ken Chu. However, construction of the unit was postponed in favor of further study of newer compression algorithms for which this unit would not be optimal.

Software simulations of first-order (one symbol memory) adaptive Huffman codes were performed, and the compression achieved was compared with that of Ziv-Lempel coding. As was expected, first-order adaptive Huffman coding (rate .643) was less effective than Ziv-Lempel coding (rate about .52). In addition, the memory requirements and computation time for first-order adaptive Huffman were significantly greater, so we have eliminated this method from future research.

5. PhD Dissertations

Following is a list of the Ph.D. Dissertations sponsored, at least in part, by this JSEP contract:

1. A. Barron, *Logically Smooth Density Estimation*. Ph. D. Th., Stanford University, Dept. of Elec. Eng., 1985.

2. Cioffi, J. M., *Fast Transversal Filters for Communications Applications*. Ph.D. Th., Stanford University, Dept., of Elec. Eng., 1984.

3. Klein, R. K., *Electron Channeling Radiation From Diamond: Theory, Experiments, and Applications*. Ph.D. Th., Stanford University, Dept. of Elec. Eng., 1985.

4. M. J. Sabin, *Global Convergence and Emperical Consistency of the Generalized Lloyd Algorithm*. Ph.D. Th., Stanford University, Dept. of Elec. Eng., 1985.

6. Publications

Following is a list of those publications sponsored, at least in part, by this JSEP contract:

1. B. L. Berman, B. A. Dahling, S. Datz, J. O. Kephart, R. K. Klein, R. H. Pantell and H. Park, "Channeling-Radiation Measurements at Lawrence Livermore National Laboratory," *Nuclear Instruments and Methods in Physics Research* B10/11 (1985) 611-617.

2. A. M. Bruckstein, T. J. Shan and T. Kailath, "The Resolution of Overlapping Echoes," *IEEE Trans. ASSP.*

3. E. S. Hellman and J. S. Harris, "Energy-Momentum Relation for Polarons Confined to One Dimension," sumbitted to Phys. Rev. B, 1985.

4. E. S. Hellman, J. S. Harris, C. B. Hanna and R. B. Laughlin, "One Dimensional Polaron Effects and Current Inhomogeneities in Sequential Phonon Emission," presented at 4th International Conf. on Hot Electrons in Semiconductors, July 1985.

5. E. S. Hellman and J. S. Harris, "Polaron Transport in Quasi-One Dimensional Semiconductor Heterostructures," presented at MSS Conf., September 1985.

6. A. K. Henning, N. Chan and J. D. Plummer, "Characterization and 2-D Simulation of Impact Ionization Current in MOSFETs Between 77K and 300K," presented at DRC, June 1985.

7. A. K. Henning, N. Chan and J. D. Plummer, "Substrate Current in N-Channel and P-Channel MOSFETs Between 77K and 300K: Characterization and Simulation," presented at IEDM, Dec. 1985.

8. T. Kailath and M. Wax, "A Note on the Complementary Model of Weinert and Desai," *IEEE Trans. Autom. Contr.*, Vol. AC-29, no.6, pp. 551-552, June 1984.

9. T. Kailath and L. Ljung, "Explicit Strict Sense State-Space Realizations of Nonstationary Gaussian Processes," *Inter'l. J. Control.*

10. R. L. Klein, J. O. Kephart, R. H. Pantell, H. Park, B. L. Berman, R. L. Swent, S. Datz and R. W. Rearick, "Electron Channeling Radiation from Diamond," *Phys. Rev. B* 31 (1) January 1985, 68-92.

11. C. E. McCants, T. Kendelewicz, M. D. Williams, R. S. List, I. Lindau and W. E. Spicer, "Ti on GaAs (110)," SSRL Users Meeting, 1985.

12. H. Park, J. O. Kephart, R. K. Klein, R. H. Pantell, S. Datz and R. L. Swent, "Electron Channeling Radiation from Diamonds with and Without Platelets," *J. Appl. Phys.* 57 (5) March 1985, 1661-1664.

13. A. Paulraj and T. Kailath, "On Beamforming in Presence of Multipath," *ICASSP '85*, Tampa, FL, March 1985.

14. A. Paulraj and T. Kailath, "Direction of Arrival Estimation by Eigenstructure Methods with Unknown Sensor Gain and Phase," *ICASSP '85*, Tampa, FL, March 1985.

15. A. Paulraj, T. J. Shan and T. Kailath, "Direction of Arrival Estimation for Signals in the Presence of Unknown Noise Fields," *ICASSP '85*, Tampa, FL, March 1985.

16. M. Sabin and R. M. Gray, "Product Code Vector Quantizers for Waveforms and Voice Coding," *IEEE Trans. ASSP*, Vol. ASSP-32, 1984.

17. T. J. Shan, M. Wax and T. Kailath, "Spatial Smoothing for Direction-of-Arrival Estimation of Coherent Sources," accepted *IEEE Trans. ASSP*.

18. M. A. Taubenblatt, C. R. Helms, "Interface Effects on Ti and Hf Schottky Barriers on Si", *Appl. Phys. Lett.* 44, 895 (1984).

19. M. Wax, T-J. Shan and T. Kailath, "Spatio-Temporal Spectral Analysis by Eigenstructure Methods," *IEEE Trans. ASSP*, Vol. ASSP-32, no. 4, pp. 817-827, August 1984.

20. M. Wax and T. Kailath, "Decentralized Processing in Passive Arrays," submitted *IEEE Trans. ASSP*.

21. M. Wax and T. Kailath, "Extending The Threshold of the Eigenstructure pMethods," *ICASSP '85*, Tampa, FL, March 1985.

22. M. D. Williams, T. Kendelewicz, R. S. List, N. Newman, C. E. McCants, I. Lindau, W. E. Spicer, "Cr on GaAs (110): The effect of Electronegativity on the Schottky Barrier Height", *J. Vac. Sci. Tech.*, in press.

23. J. C. S. Woo and J. D. Plummer, "Short Channel Effects in MOSFETs at Liquid Nitrogen Temperature," submitted to IEEE Trans. Electron Devices for publication

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